



## SENSITIVITY AND ACCURACY OF THE MEASUREMENT WITH THE YOKE COIL OF THE DOUBLER DIPOLE

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In Fig. 1 is shown the qualitative flux pattern in the Doubler dipole with the symmetry plane of the field slightly rotated with respect to the separating plane between the half yokes. Flux,  $\phi_i$  and  $\phi_a$ , passing inside and outside the yoke coil respectively will be distributed according to the particular gap shape between the half yokes and hence affect yoke coil calibration as pointed out by A.Tollestrup\*.

In this note the present configuration and modifications of the immediate iron surroundings of the yoke coil will be quantitatively examined with respect to their effect on sensitivity and accuracy of the yoke coil.

Almost all flux,  $\phi_b$ , passing the plane of the yoke coil in the yoke bore where  $\mu = 1$  will return through the yoke. There it will branch into fluxes  $\phi_i$  and  $\phi_a$  (Fig. 1) not linking and linking the coil respectively so that the net flux through the coil is:

$$\phi_a = \phi_b - \phi_i. \quad (1)$$

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\*"The Amateur Magnet Builder's Handbook", Sect. 1-7, UPC No. 86

The sensitivity,  $S$ , for measuring relative rotation between magnetic field direction and parting plane of the yoke is proportional to the fraction of the flux passing the yoke coil. For  $\phi_i = \phi_b$  (coil located outside iron) the sensitivity will be zero. For  $\phi_i = 0$  (coil just inside yoke bore) it will have its maximum value  $S_0$ . For intermediate locations of the yoke coil:

$$S = S_0 \frac{1}{1 + \frac{\phi_i}{\phi_a}} \quad (2)$$

The relatively small reluctances (in two dimensions)

$$R_i = \frac{L_i}{\mu_0 i} \text{ and } R_a = \frac{L_a}{\mu_0 a} \quad (\text{see Fig. 2})$$

determine the ratio of the fluxes  $\phi_i$  and  $\phi_a$ . Their effect on the total flux is negligible (bore's large reluctance in series). In the iron  $\phi_a$  has a longer path than  $\phi_i$  and therefore greater reluctance. With pathlength difference  $\approx .2"$  and zero field permeability in the iron  $\approx 200$ , the difference in reluctance corresponds to the reluctance of an airgap of  $.001"$ , is systematic and will, therefore, be neglected. The reluctance of the groove for the yoke coil is at least a factor 100 greater than  $R_a$ , so that negligible flux will pass through the groove. Variation of coil position in the groove will therefore have negligible effect on the sensitivity of the angle measurement with the yoke coil.

On the other hand a small difference between  $L_a$  and  $L_i$  will have a large effect on the sensitivity. From (2) since  $\phi \sim 1/R$ :

$$S = S_0 \frac{1}{1 + \frac{i \cdot L_a}{L_i \cdot a}} \quad (3)$$

with  $2i \approx a$  one obtains for parallel inner and outer gaps:

$$S = S_0 \frac{1}{1 + \frac{L_a}{2L_i}} \quad (4)$$

#### SENSITIVITY OF PRESENT CONFIGURATION

The existing yoke configuration has inner and outer gaps small and about equal (Fig. 2). A strong dependence of  $S/S_0$  on small changes of inner or outer gap is apparent from Graph 1. Table I shows this dependence for a few selected values of  $L_a$  and  $L_i$ . For small equal inner and outer gaps the relative sensitivity is .67 independent of the gap height. The larger the gap, the smaller is the departure from .67. If one assumes the average gap to be .002"  $S/S_0$  will vary between .57 and .80, if the outer gap is increased and decreased by .001" respectively.

One might argue, the precision of the stamped yoke laminations precludes variation of  $L_a$  by as much as .001" from one yoke to the next. However, the tiestrap joining the half yokes also conducts a certain amount of flux which is uncertain because the gap between it and the yoke is uncertain to the extent of several thousandths of an inch. Therefore, even for equal inner and outer gaps, the relative sensitivity may vary strongly because of the tiestrap.

#### POSSIBLE IMPROVEMENT OF SENSITIVITY AND ACCURACY

From (3) it is clear that for a large relative sensitivity  $i$  and  $L_a$  should be as small as possible. If one, in addition, increases  $a$  and  $L_i$ , the relative sensitivity will increase still more while its error due to a small change in  $L_i$  decreases.

A simple modification would be to leave the yoke coil where it now is and to increase  $L_i$ . A yet greater improvement would be to

provide a new location for the yoke coil as shown in Fig. 3. With the nomenclature of Fig. 2, the ratio  $\frac{i}{a}$  in equation (3) is limited mainly by the requirement of reasonable mechanical stability of the .025" x .050" ridge. The requirements on  $L_i$  are that the change of the magnetic field produced by the slot be tolerable, that the wire be retained, and that  $L_i$  be large enough so that  $S/S_0$  becomes sufficiently insensitive to small changes of  $L_i$ . For the configuration of Fig. 3 with  $L_a = .003" \pm .002$ ,  $L_i = .050"$ ,  $i = .05"$  and  $a = .65"$

$$S/S_0 = .9954 \pm .003$$

the error of  $S/S_0$  due to small changes in  $L_i$  being much smaller by comparison. The real value of relative sensitivity will be slightly lower because the reluctance of the iron in the path of  $\phi_a$  was assumed to be zero.

#### WHAT BENEFITS FROM THE MODIFIED YOKE COIL GEOMETRY?

Three advantages of an increase of sensitivity and accuracy of the yoke coil can be seen.

The least important is improved accuracy of aligning the magnetic vertical plane with the yoke coil during assembly of the yoke. This alignment is not critical, because, after the introduction of reference lugs on the yoke after magnetic measurements to define the vertical plane, the orientation of the magnetic field with respect to the yoke has become relatively uncritical.

Secondly, the yoke coil will be better suited to investigate rotation of the vertical plane during cooldown-warmup cycles, pulses and quenches. During these tests the yoke is subjected to

strain (bending) during cooldown\* which might alter the relative sensitivity of the yoke coil with the present configuration, but would leave it unchanged with the modified geometry. Moreover the relative sensitivity would be uniform to better than one percent over all magnets, and could be used to check the stretched-wire measurement of the vertical plane or replace it.

Finally, with a sectioned yoke coil\*\* to allow measurement of vertical plane rotation as a function of position along the magnet, one would have nearly constant sensitivity for all coil sections. This is a prerequisite for determining how much the collared coil twists and/or rotates as a whole with respect to the yoke during the different modes of magnet operation, because these effects may be small.

Thirdly, the stability of the calibration of the yoke coil under transport and operation of the magnets will make the yoke coil a handy instrument for measuring possible rotation of the vertical plane relative to the yoke on magnets already in the ring, or for verifying that no such rotation has occurred.

#### PRACTICAL CONSIDERATIONS

The wire for the yoke coil should have insulation to which epoxy will adhere, so that the wire may be fixed in its groove.

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\*As measured by Carlos Hojvat, Fermilab.

\*\*George Biallas, Fermilab, originated the idea of sectioning the yoke coil longitudinally.

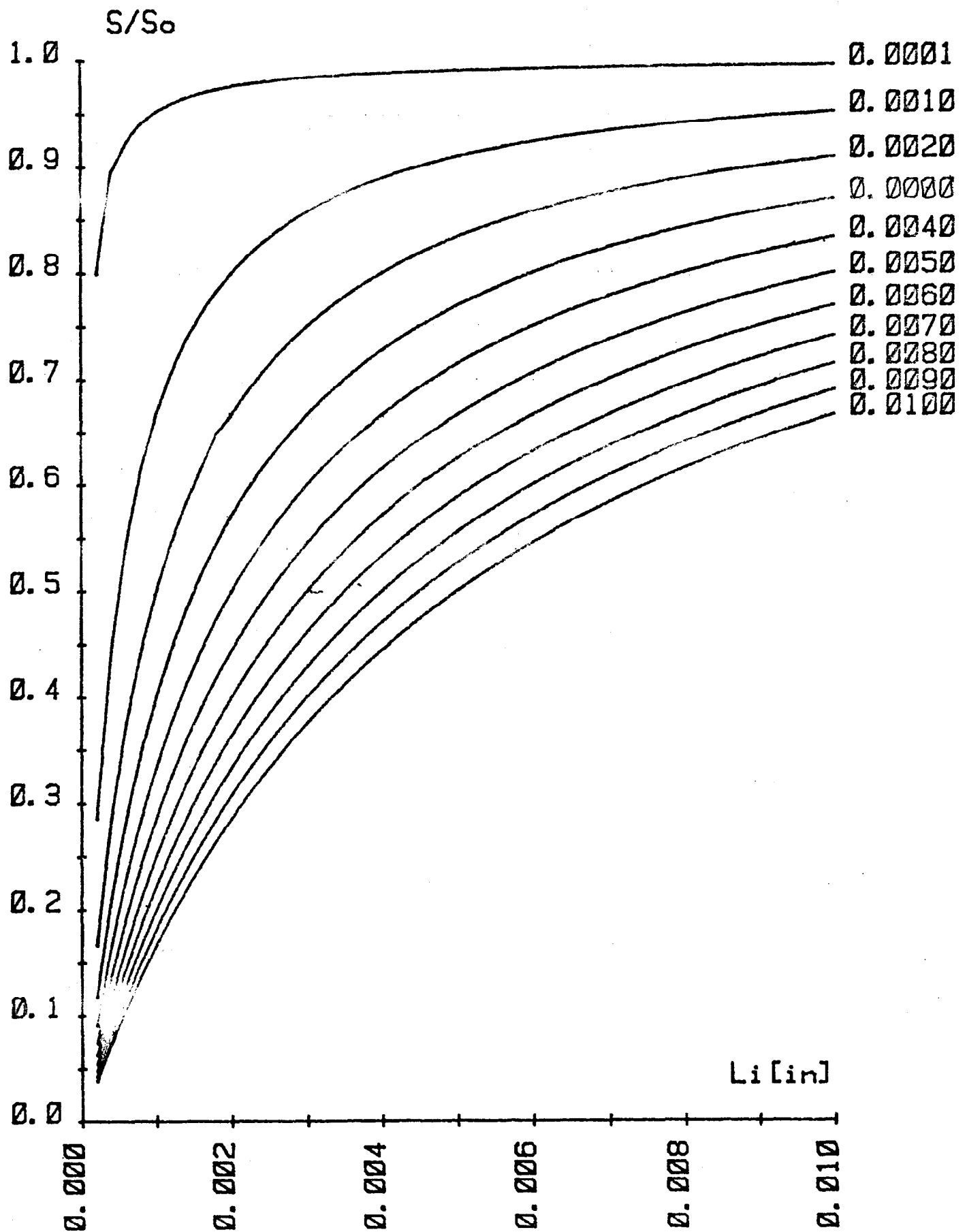
Since the sectioned coil is intended as a diagnostic tool, five symmetrically placed sections, each 42" long, should be installed into one half-core of a magnet. The other half core can be fitted with a continuous coil (Fig. 3). Until vertical plane instability is fully understood and corrected the sectioned yoke coil would be valuable for every magnet produced. Later, only the continuous coil would be needed.

The fabrication of the groove for the coil is a little involved for the yokes already completed. For the remaining yokes the groove could be inexpensively produced by merely modifying the punching die for the yoke lamination.

Should the induced voltage in the yoke coil section be too small for being accurately measured, the number of turns of the coil can easily be increased by using a multifilament wire.



La[in] =



GRAPH 1 RELATIVE SENSITIVITY AS FUNCTION OF  
SMALL INNER AND SPECIFIC OUTER GAPS



La[in]	Li[in]	S/S <sub>o</sub>			
		$\Delta L_a = +.001\text{in}$	$\Delta L_a = -.001\text{in}$	$\Delta L_i = -.001\text{in}$	$\Delta L_i = +.001\text{in}$
.001	.001	.50	1.00	0	.80
.002	.002	.57	.80	.59	.75
.003	.003	.60	.75	.57	.73
.004	.004	.62	.73	.60	.71

TABLE I  
RELATIVE SENSITIVITY OF EXISTING CONFIGURATION

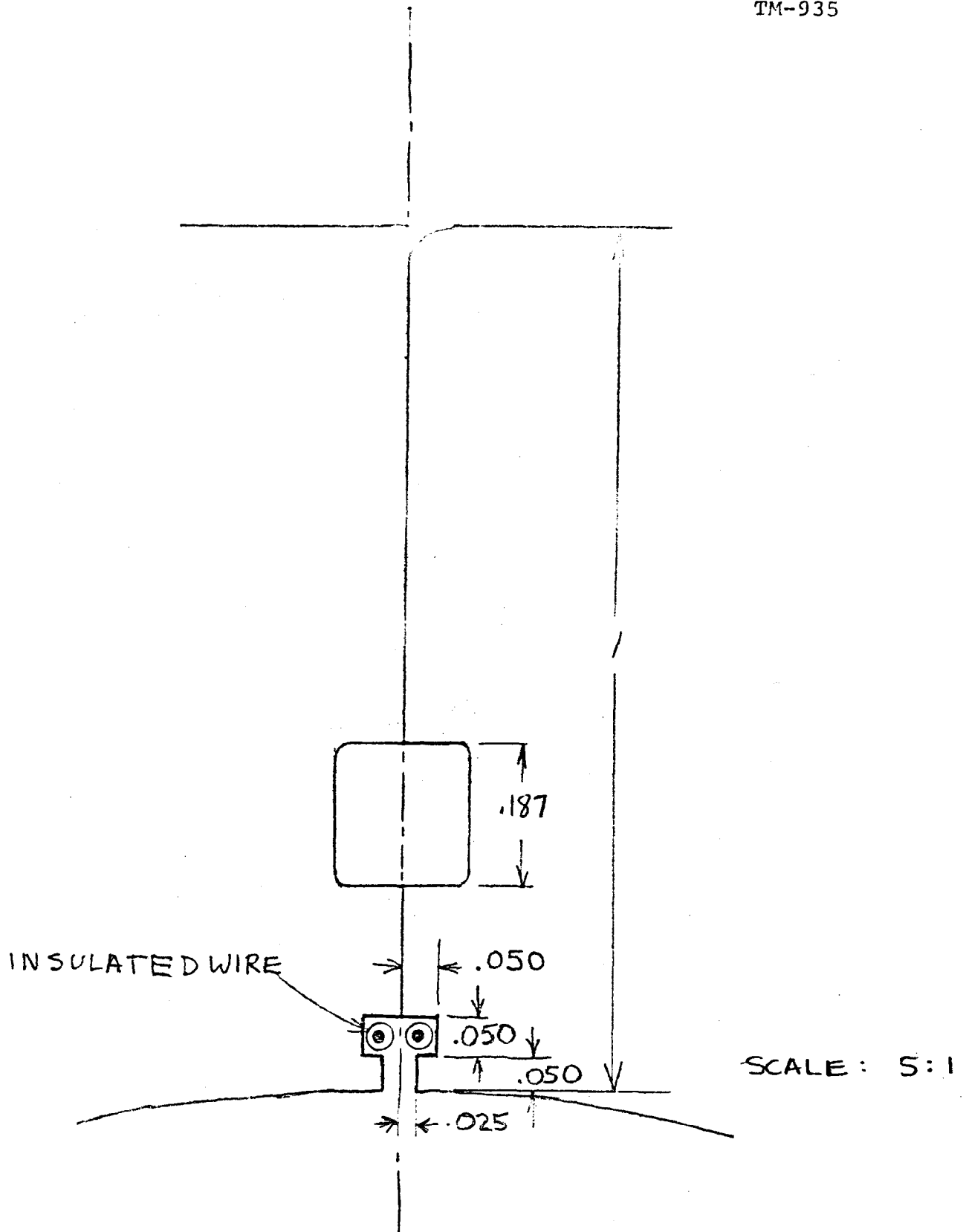


FIG 3 PROPOSED YOKE-COIL  
GEOMETRY